D-brane Inflation in String Theory and its Cosmological Footprints

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México, 12 Enero 2011

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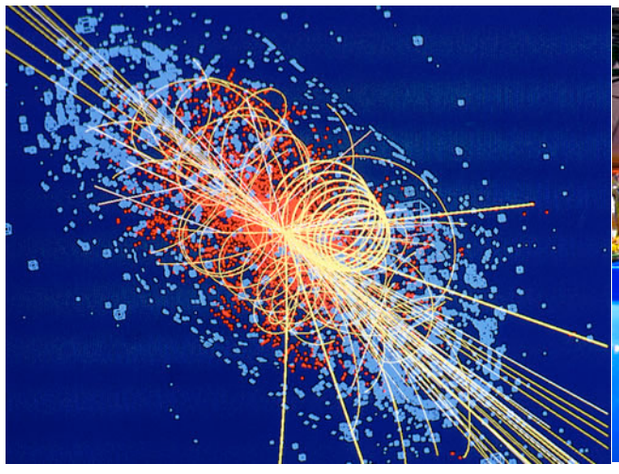

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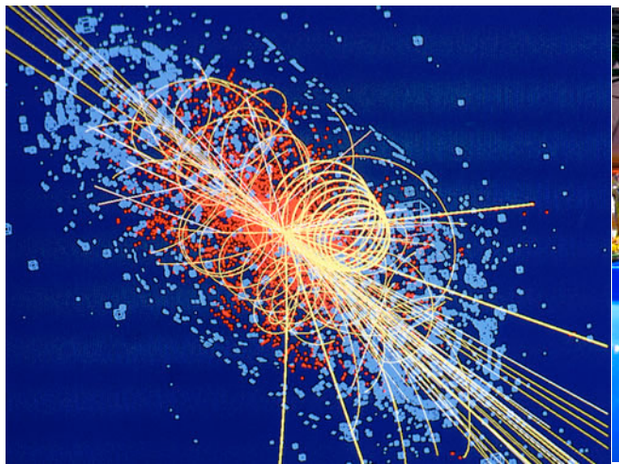

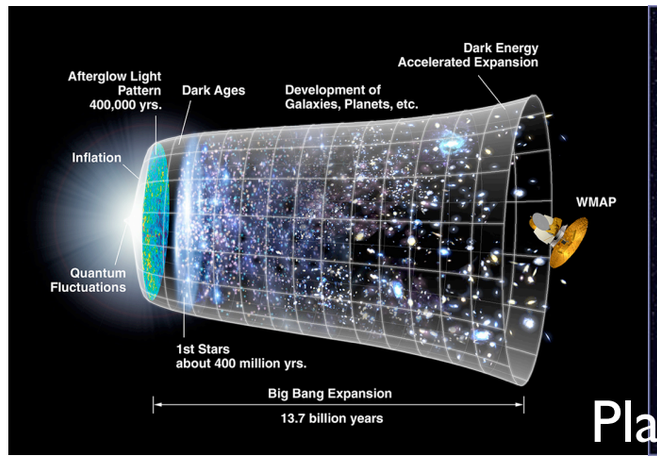

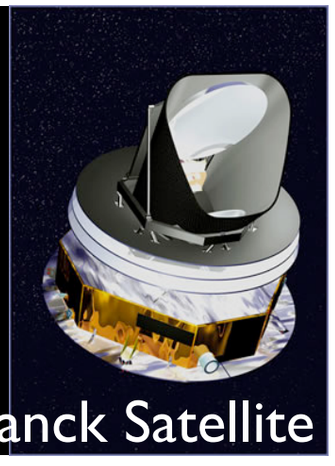

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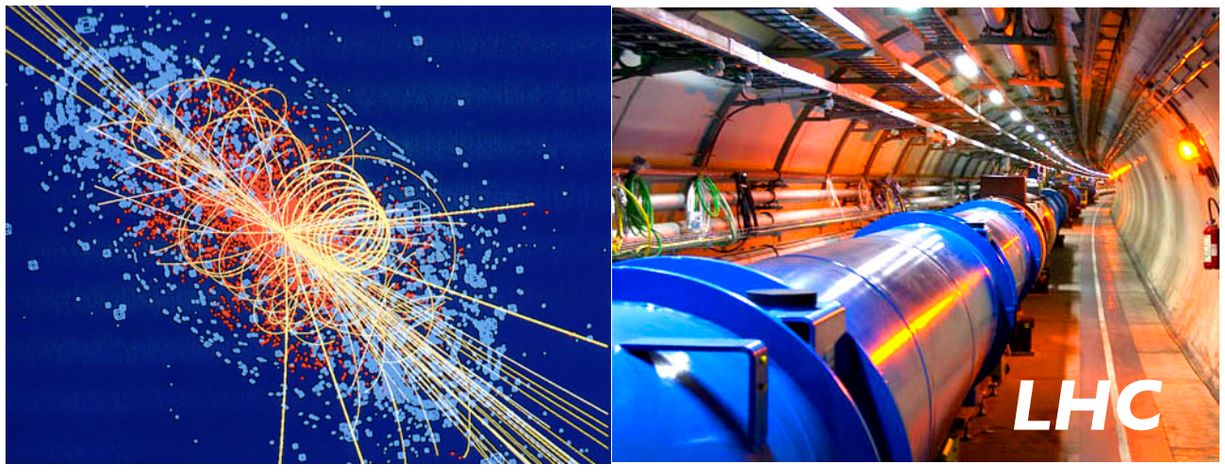

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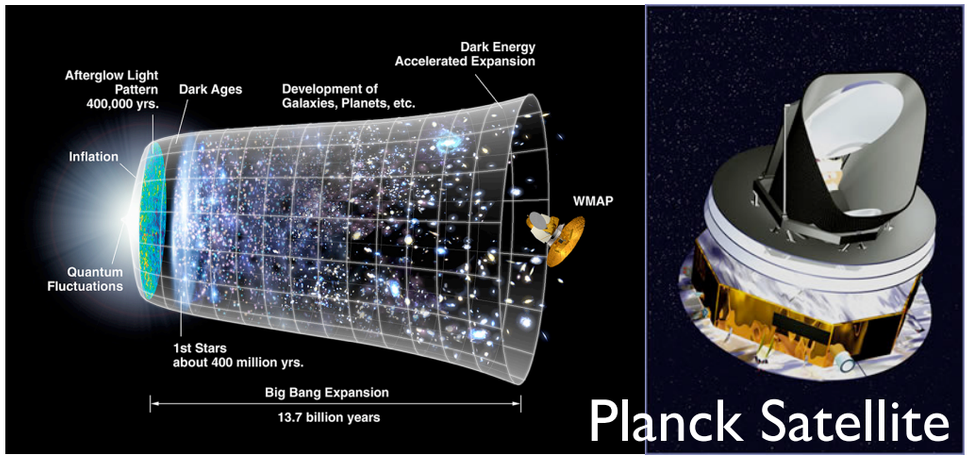

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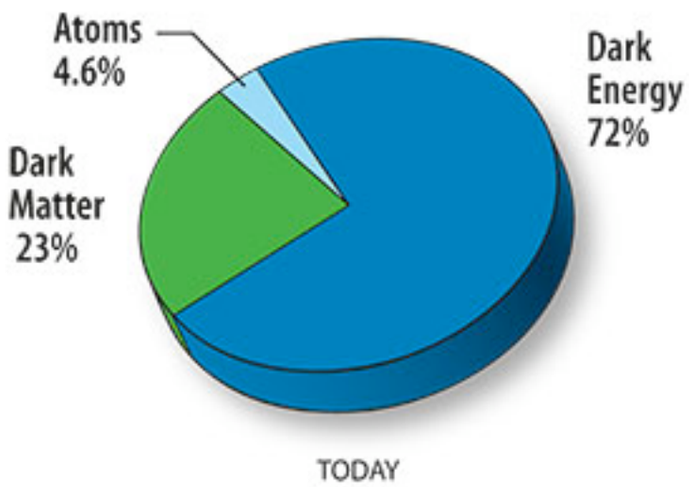
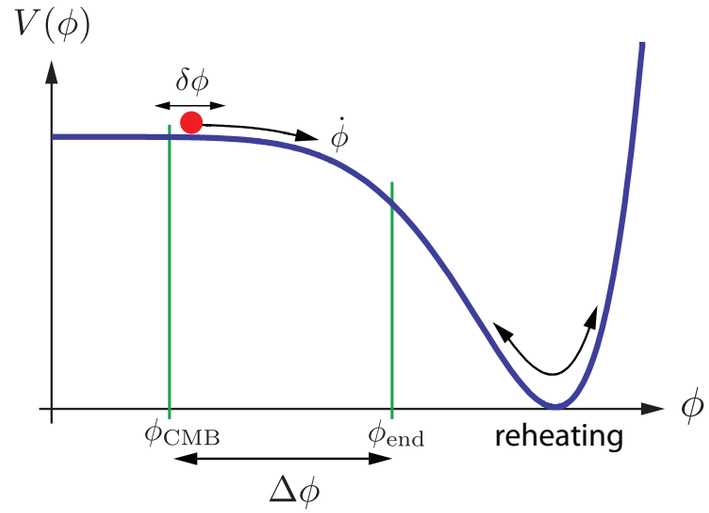
- Current observations support ΛCDM* model, complemented with inflationary paradigm, to generate the primordial perturbations that seed the large structures we observe





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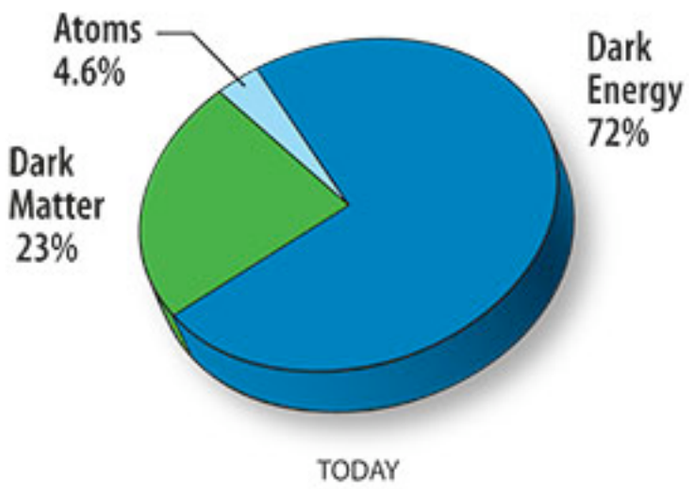

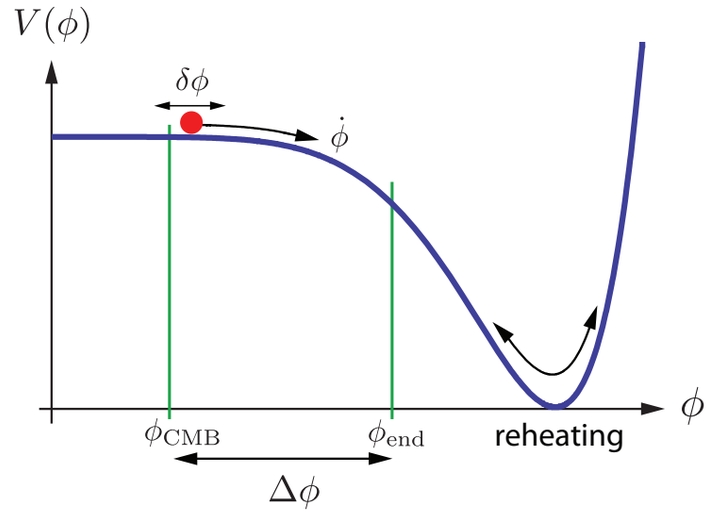

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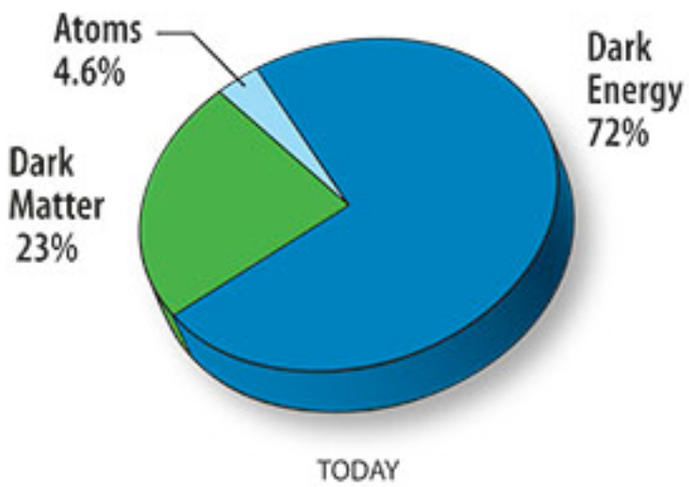

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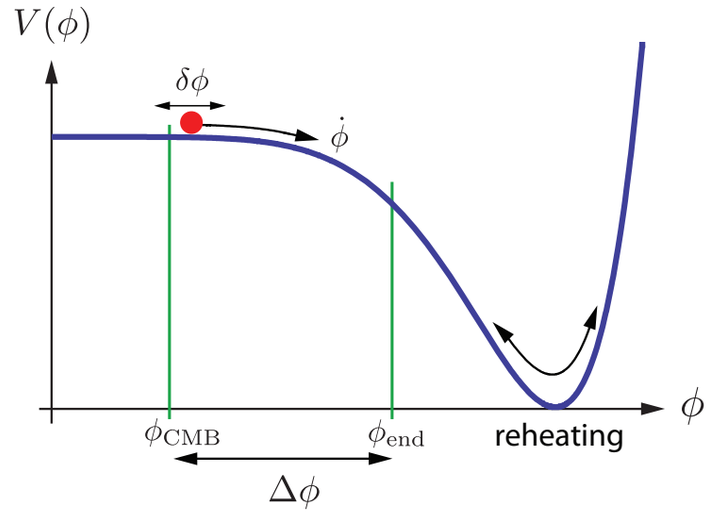

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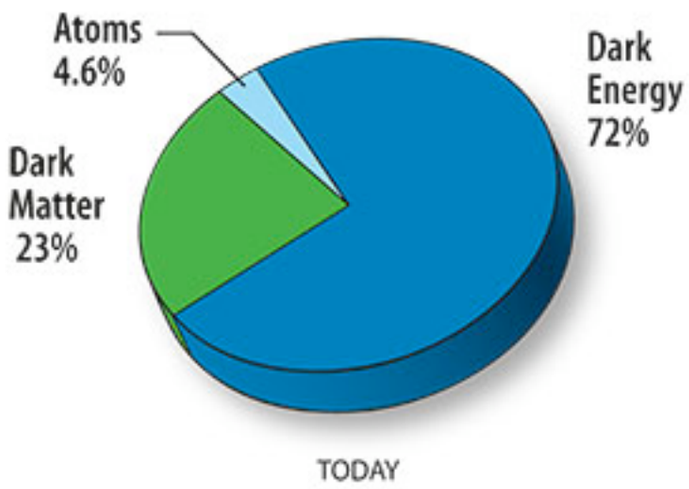

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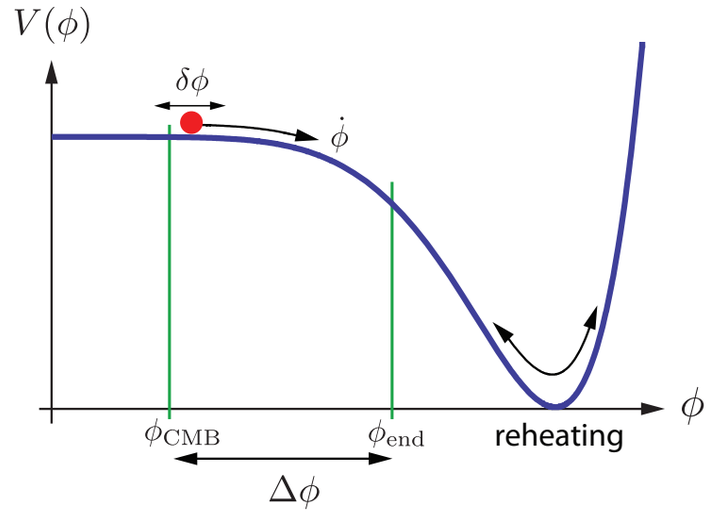

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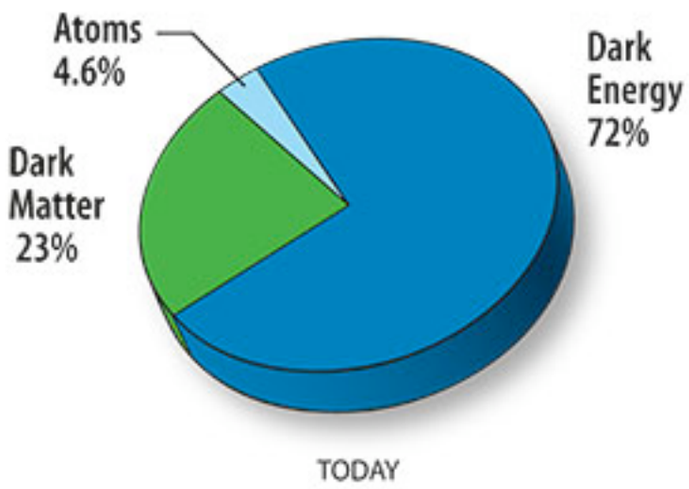

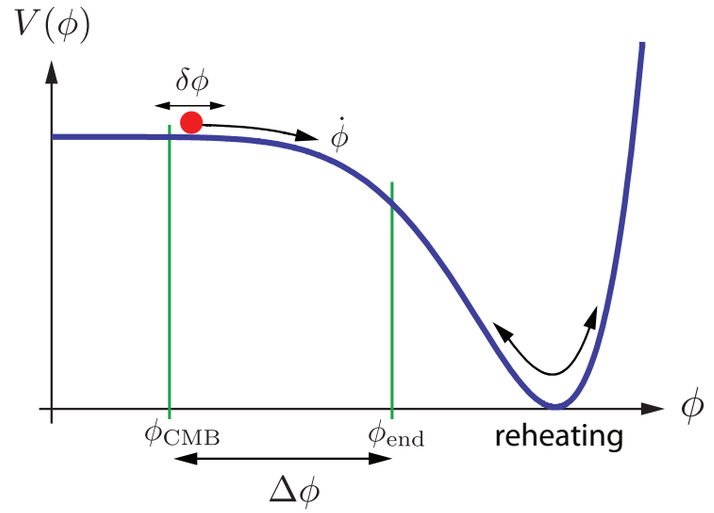

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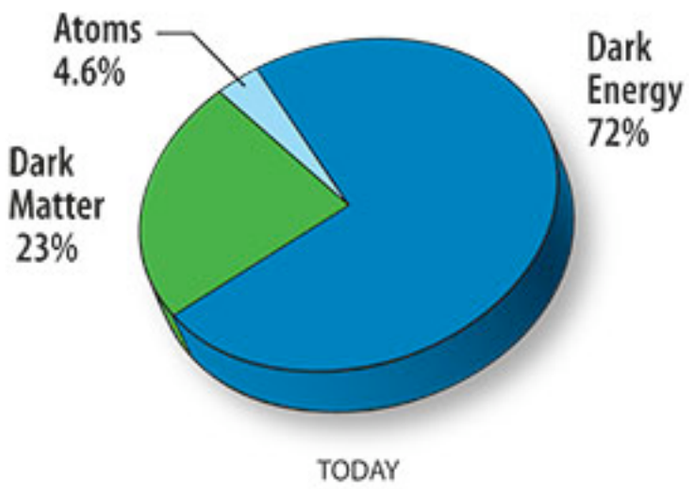

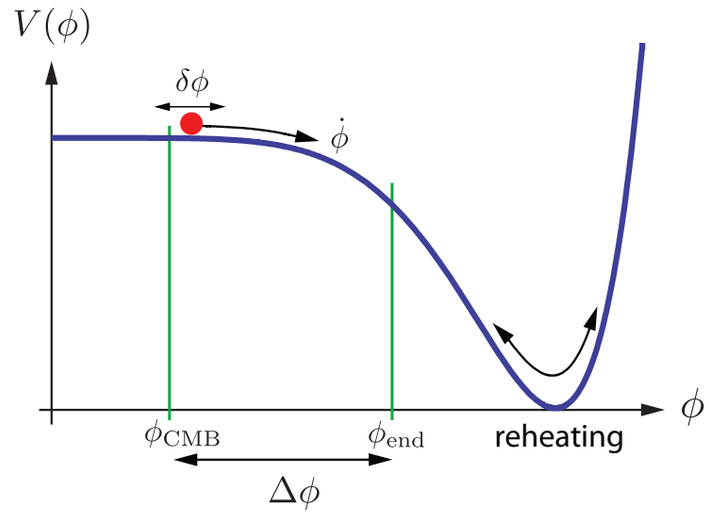

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D-brane Inflation

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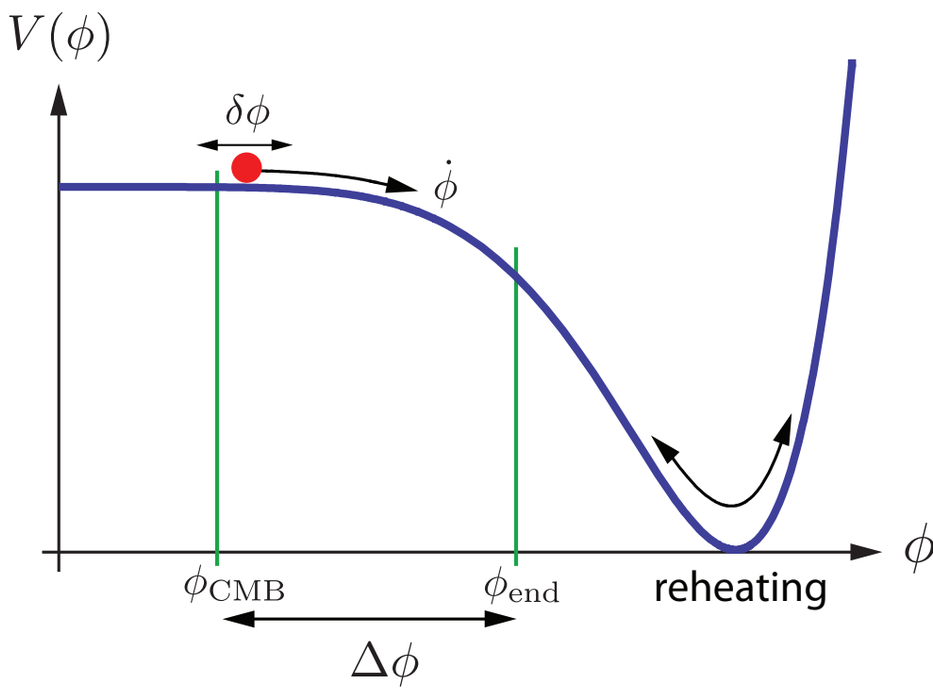
The Inflationary Paradigm

• A period of quasi exponential accelerated expansion in the very early Universe due to vacuum energy domination.

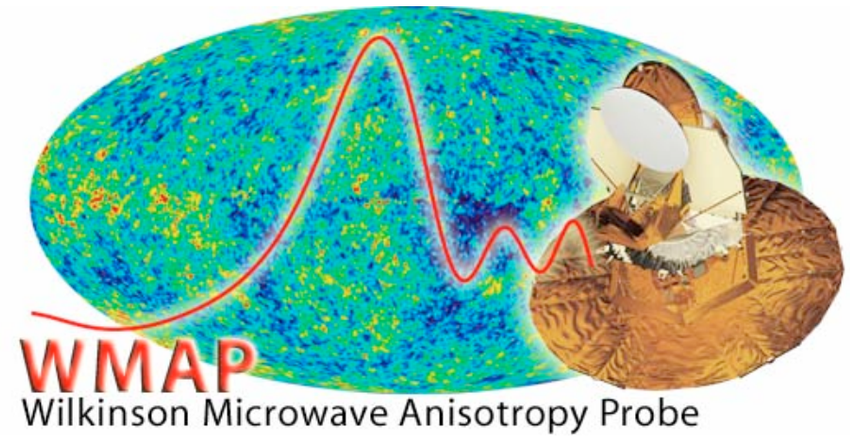
• Governed by the dynamics of a scalar field with very flat potential.



• Explains why the Universe is approximately homogeneous and spatially flat.

• Can explain the absence of relic particles and defects predicted by fundamental physics.

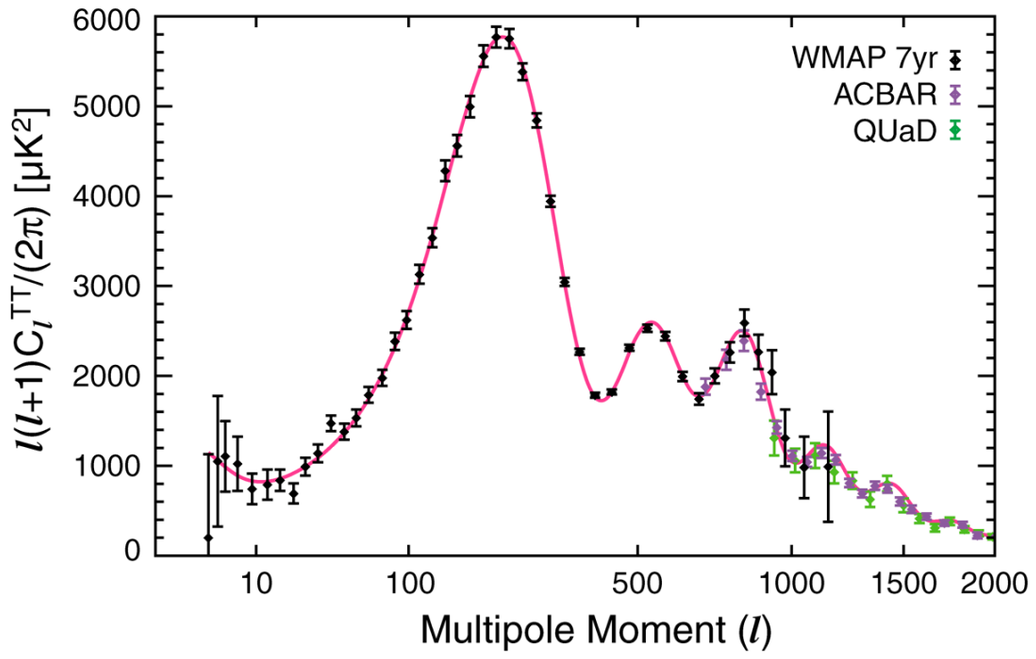
• Leading mechanism to explain observed inhomogeneities in the Universe: provides the seeds for large scale structure formation. Fluctuations of $\delta\phi \longrightarrow$ fluctuations of energy density $\delta\rho \longrightarrow$ temperature fluctuations δT in the CMB (Cosmic Microwave Background).



- Simplest inflationary model

  - single scalar field with very flat potential in a flat Universe

  - nearly scale invariant adiabatic Gaussian spectrum of scalar perturbations. In good agreement with observations of the CMB (WMAP)



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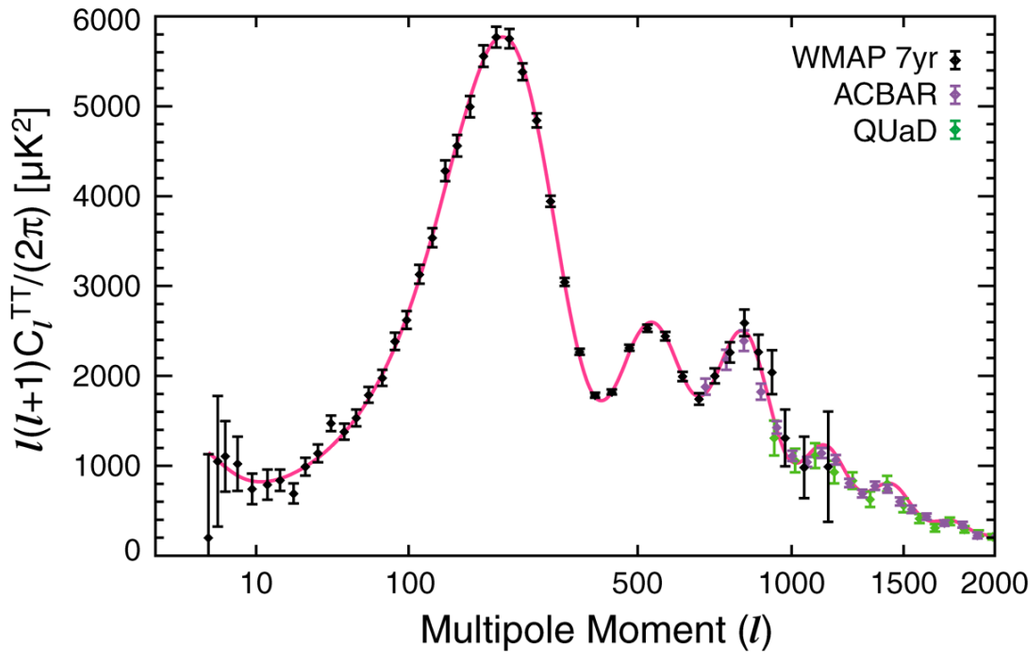

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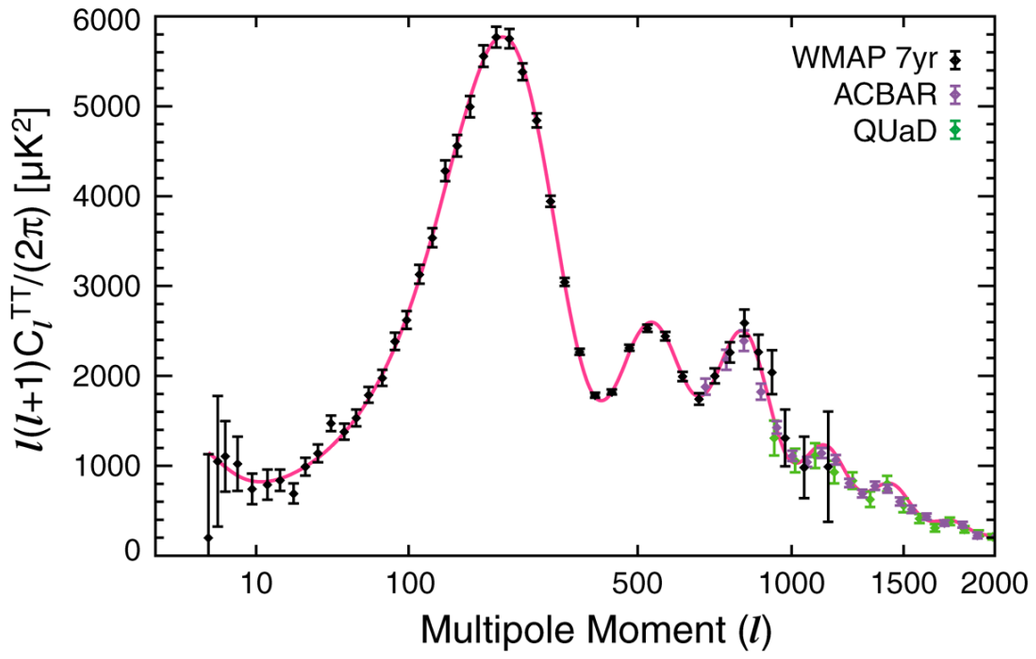
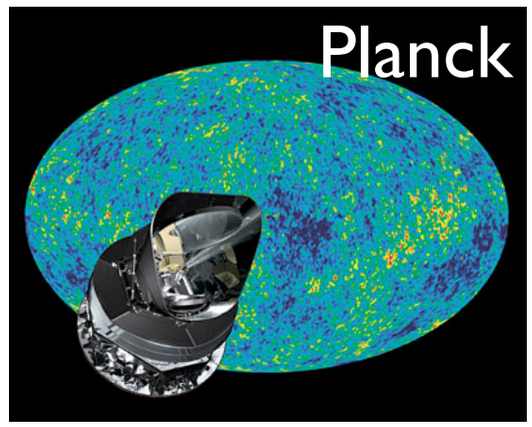


- More complex inflationary models can produce observables, accessible in forthcoming experiments such as Planck mission:

  - ✳ Observable spectrum of (primordial) gravitational waves $r \gtrsim 10^{-2}$
  - ✳ Significant non-Gaussianity $-10 < f_{NL} < 50$
  - ✳ Scale dependence of the spectral index $-0.084 < \frac{dn_s}{d\ln k} < 0.02$
  - ✳ Isocurvature density perturbations
  - ✳ Anisotropies in the spectrum



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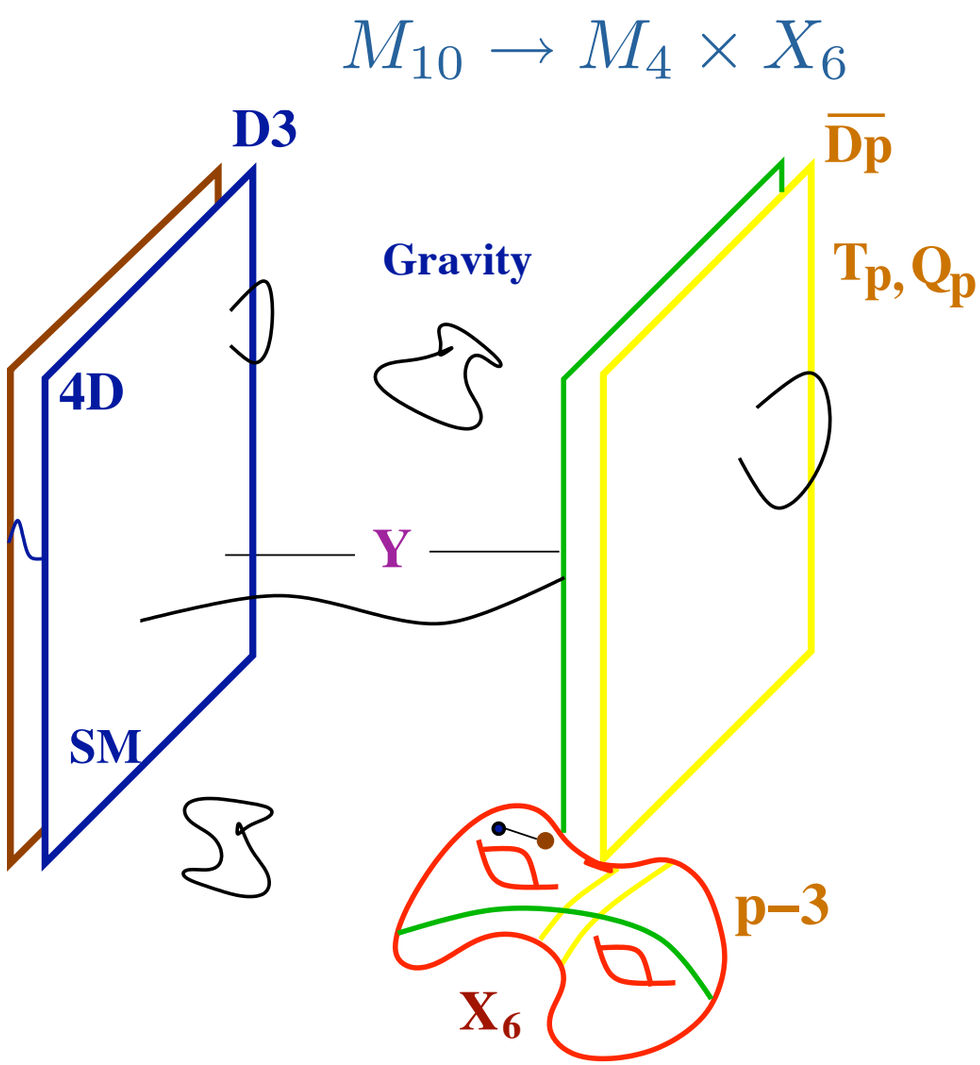

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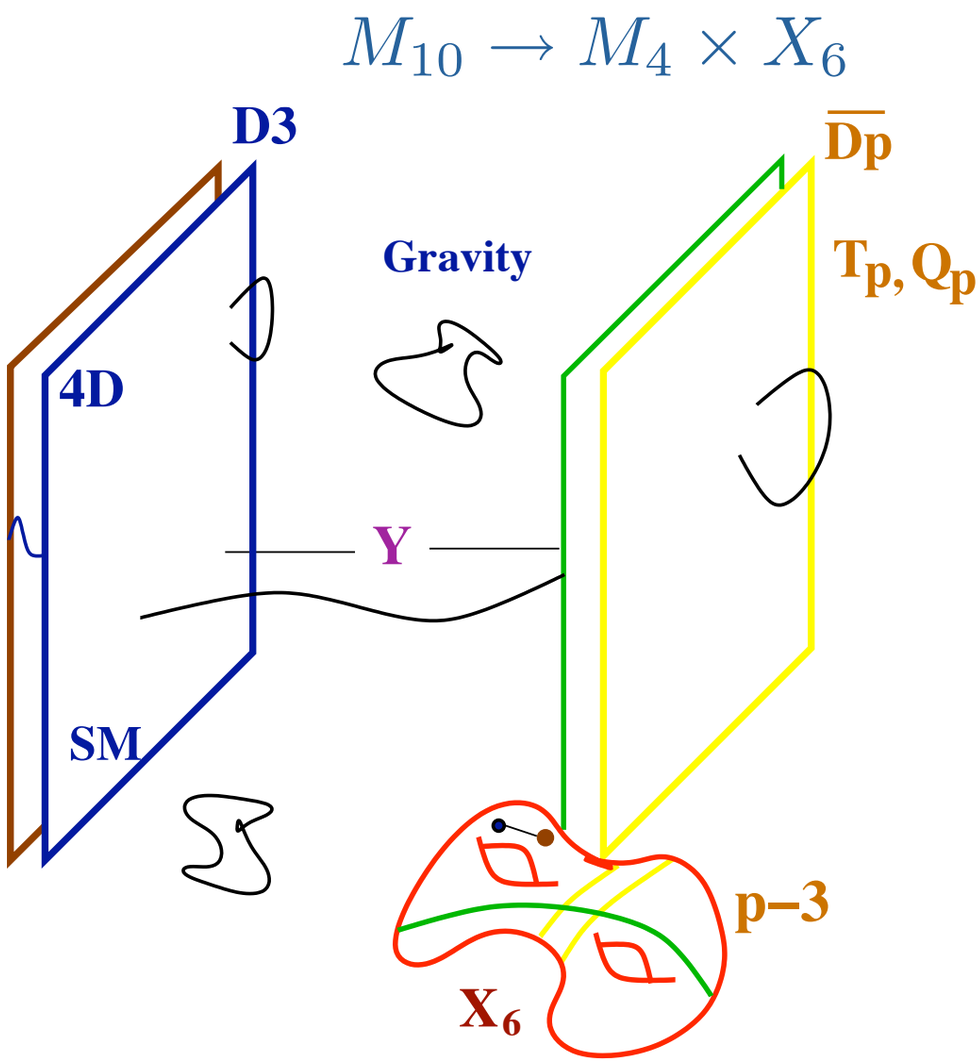

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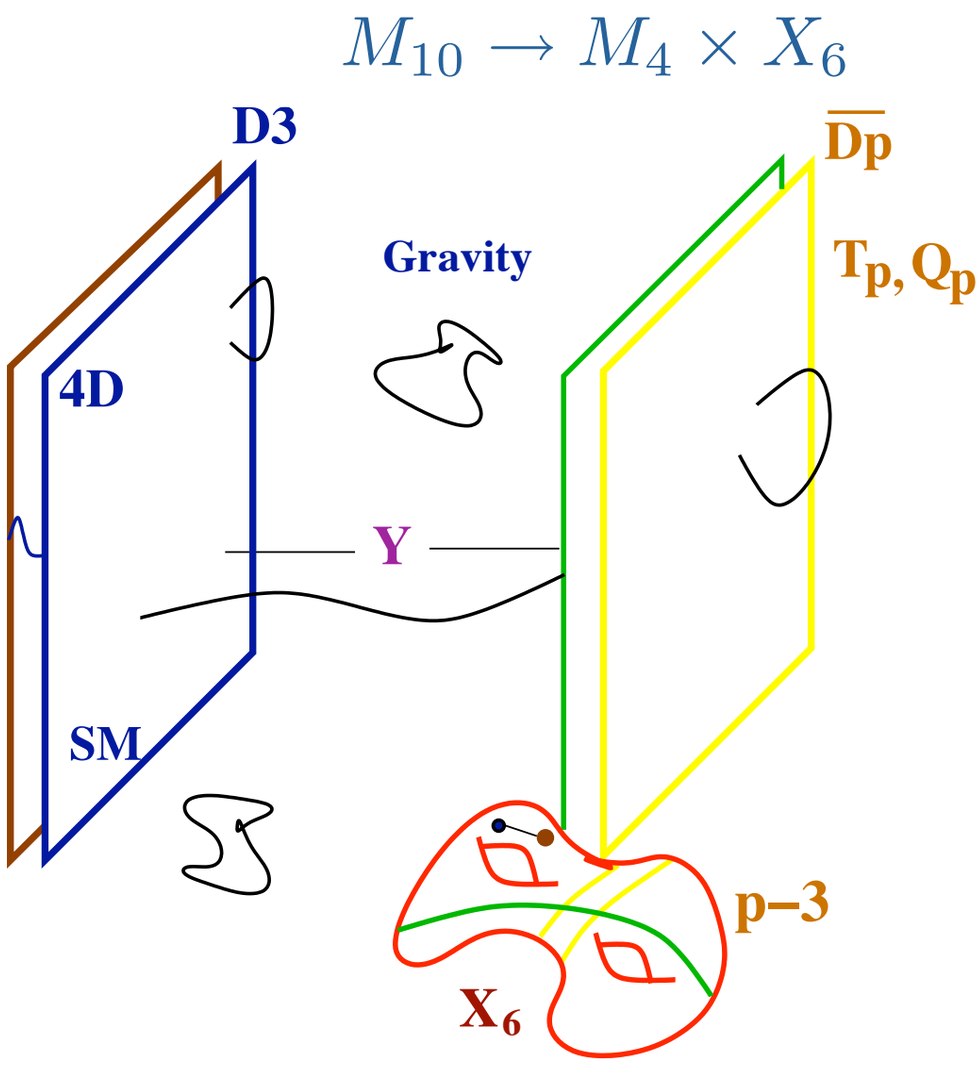

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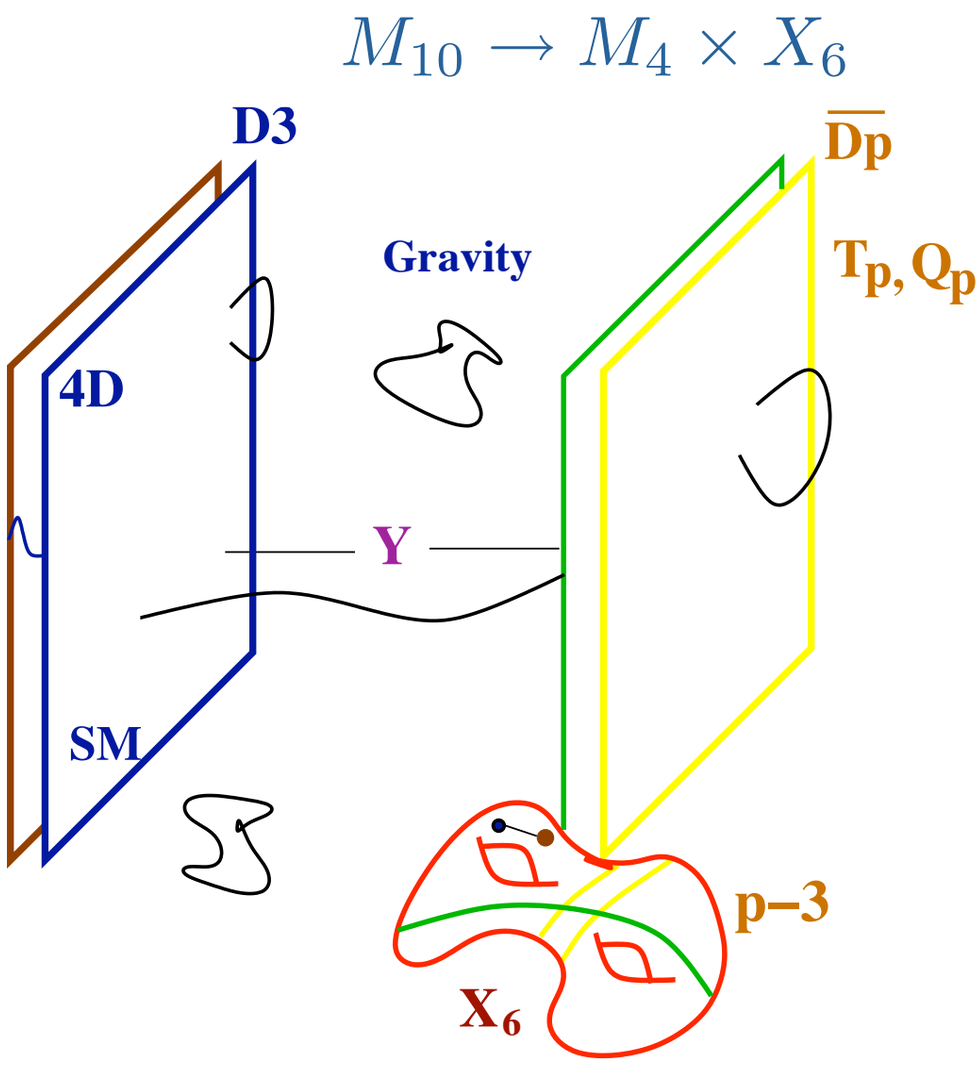

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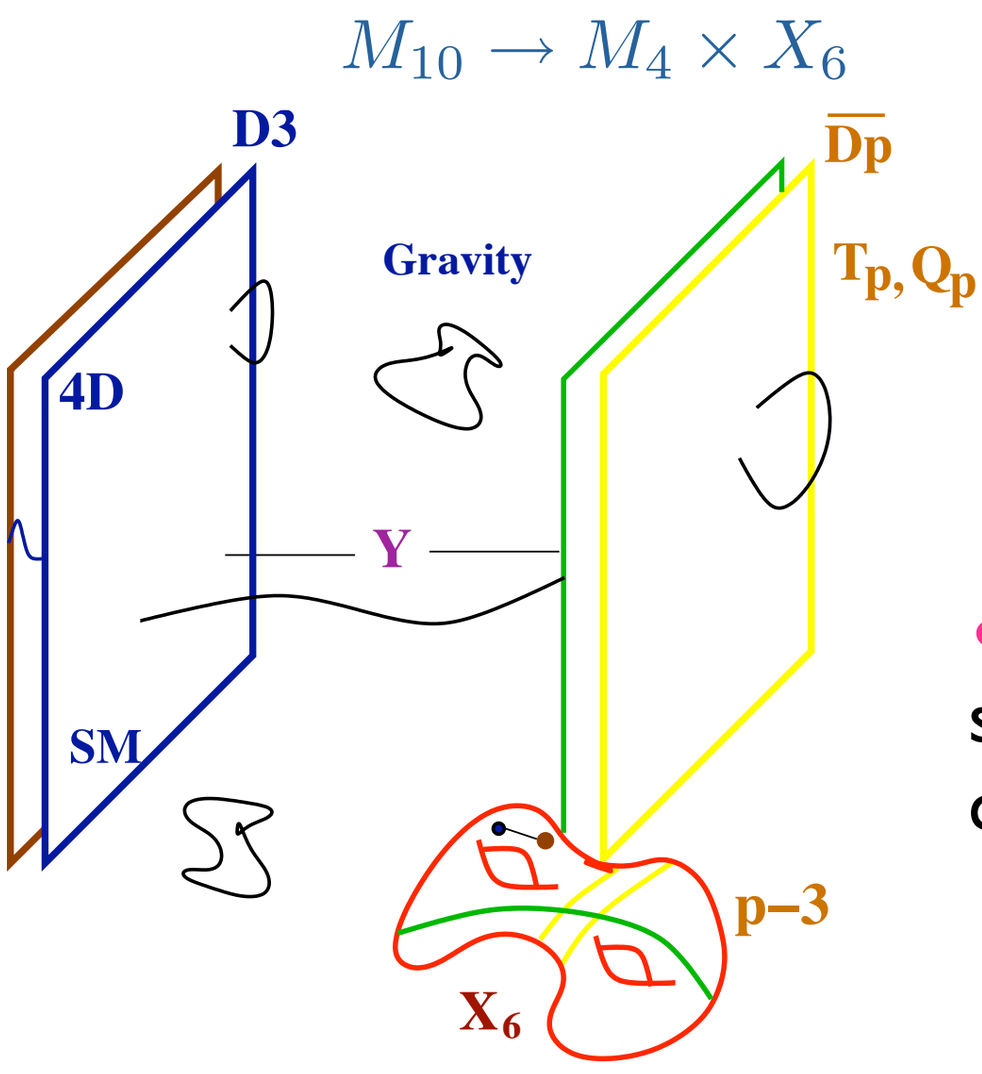

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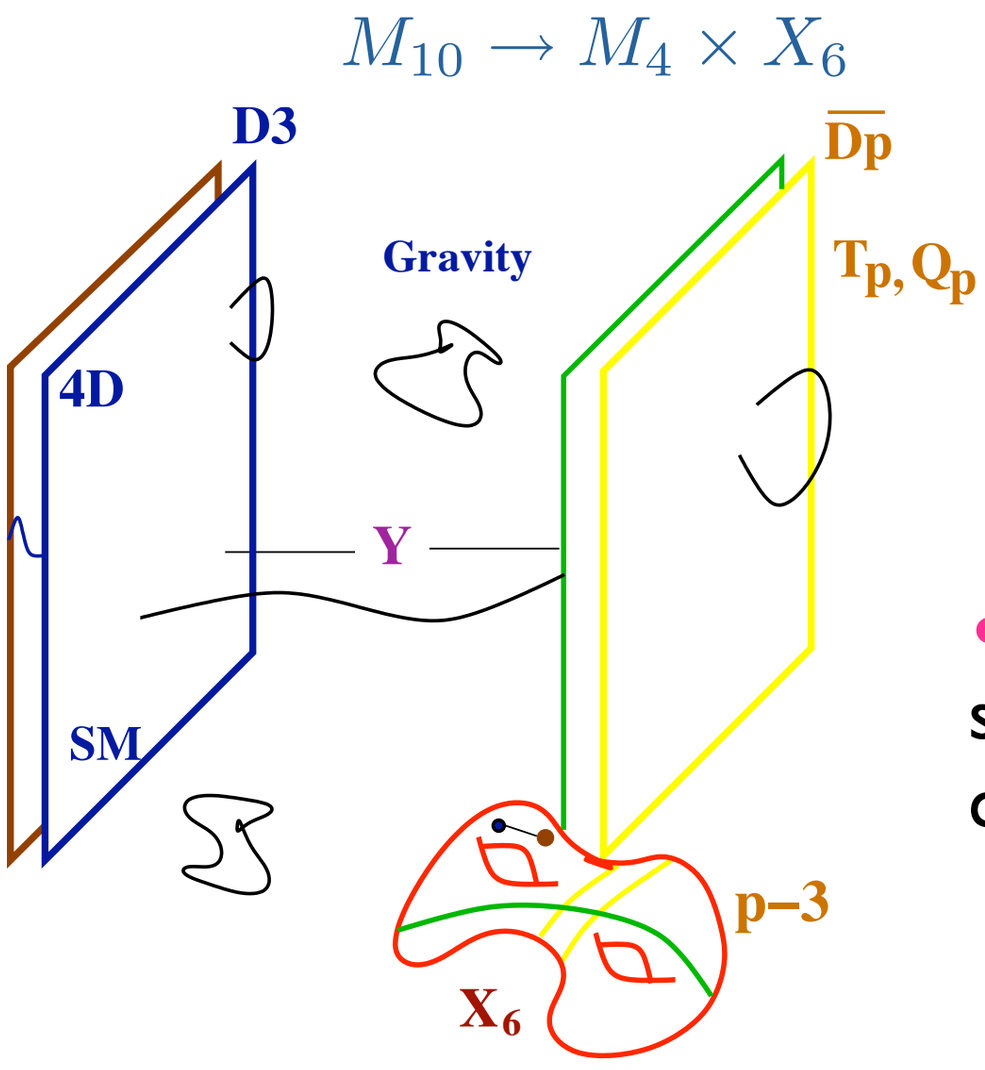

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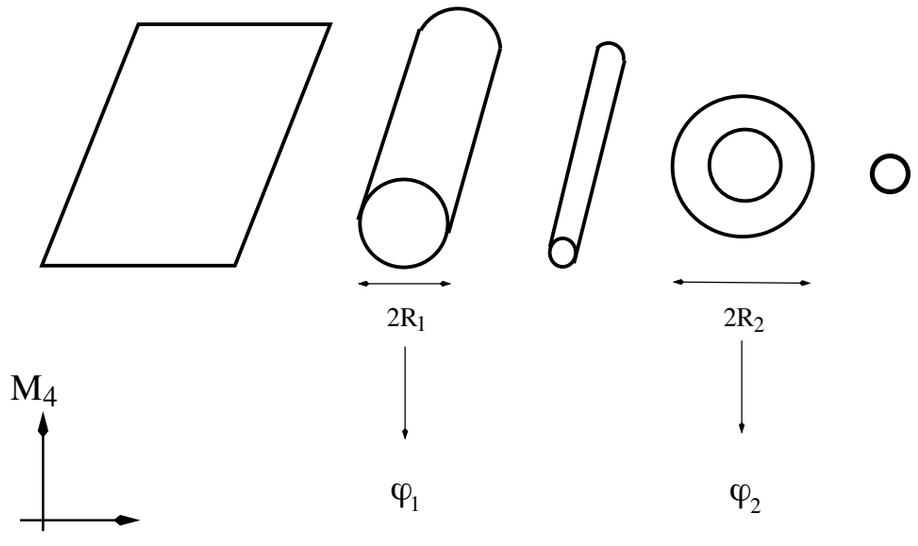

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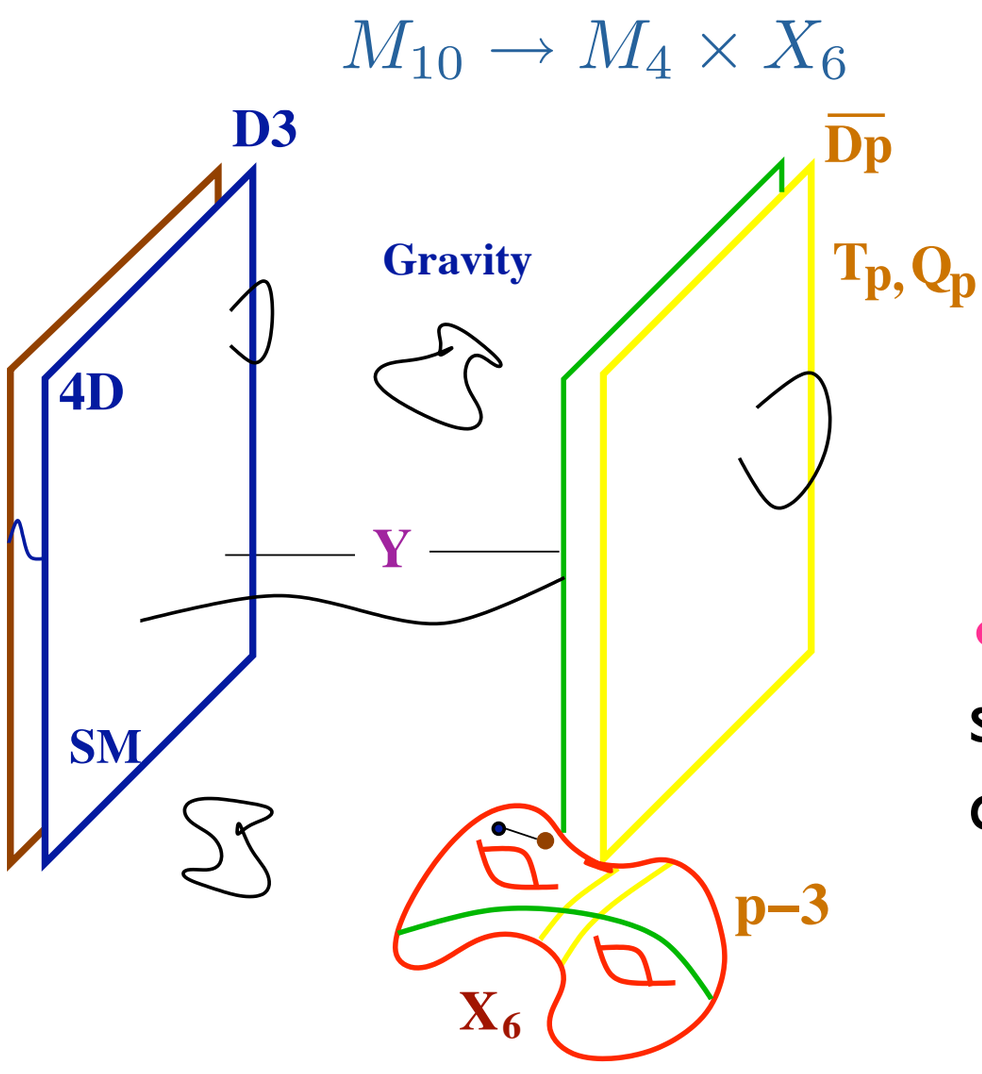

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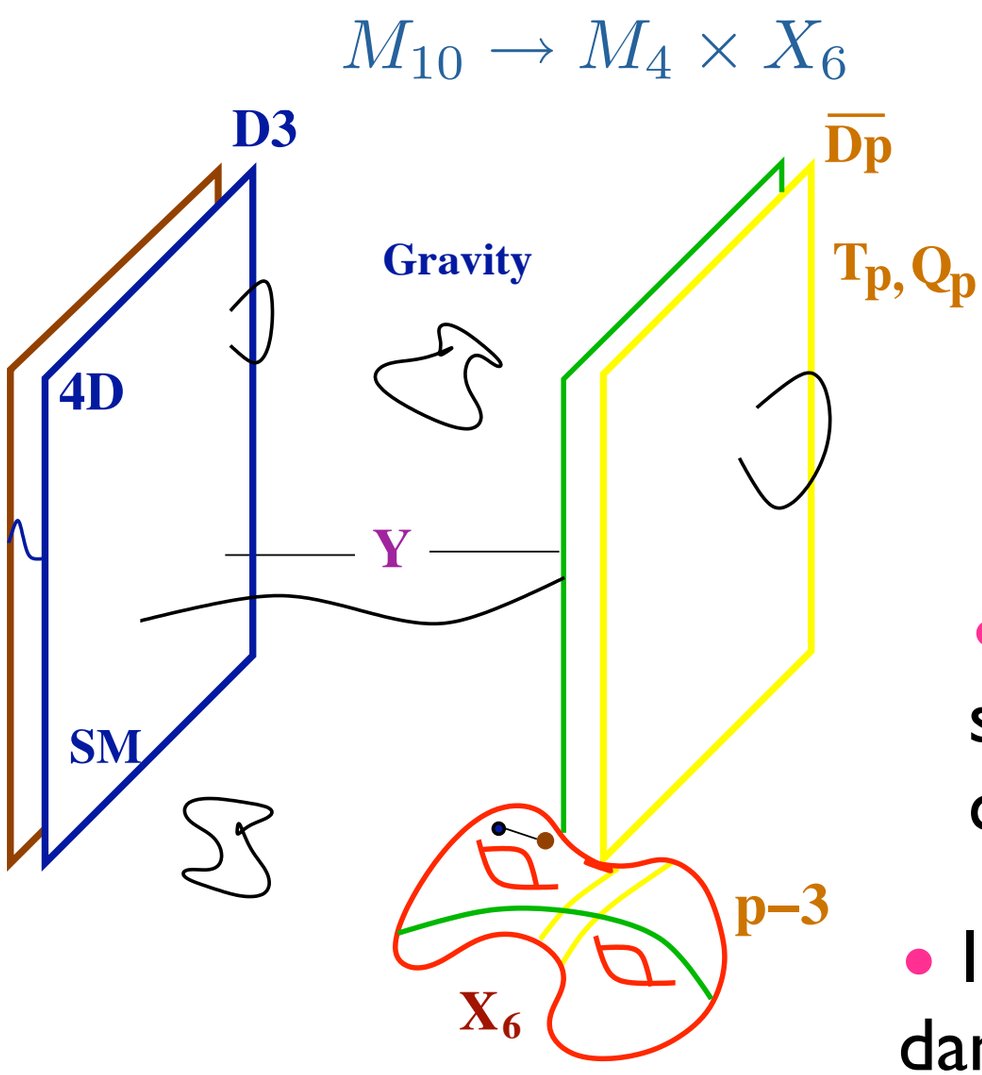

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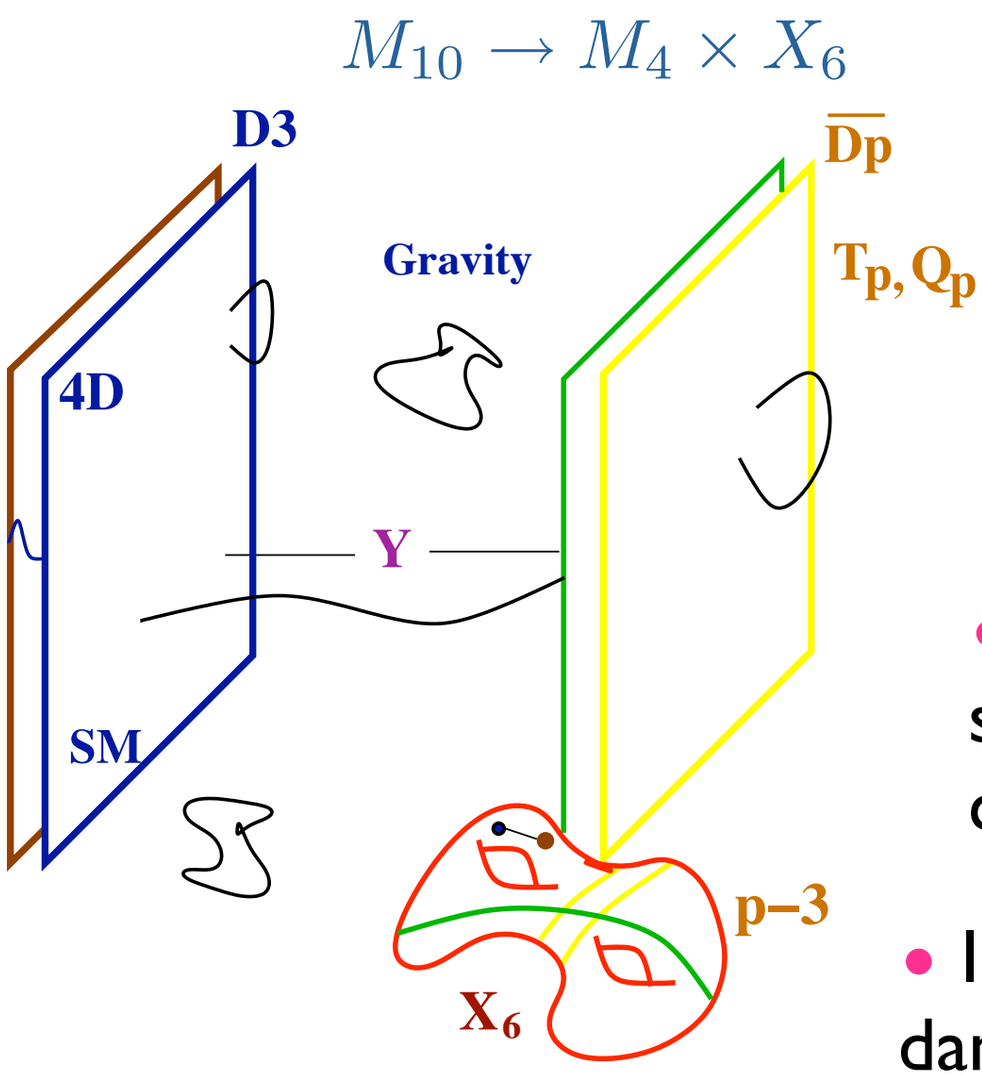

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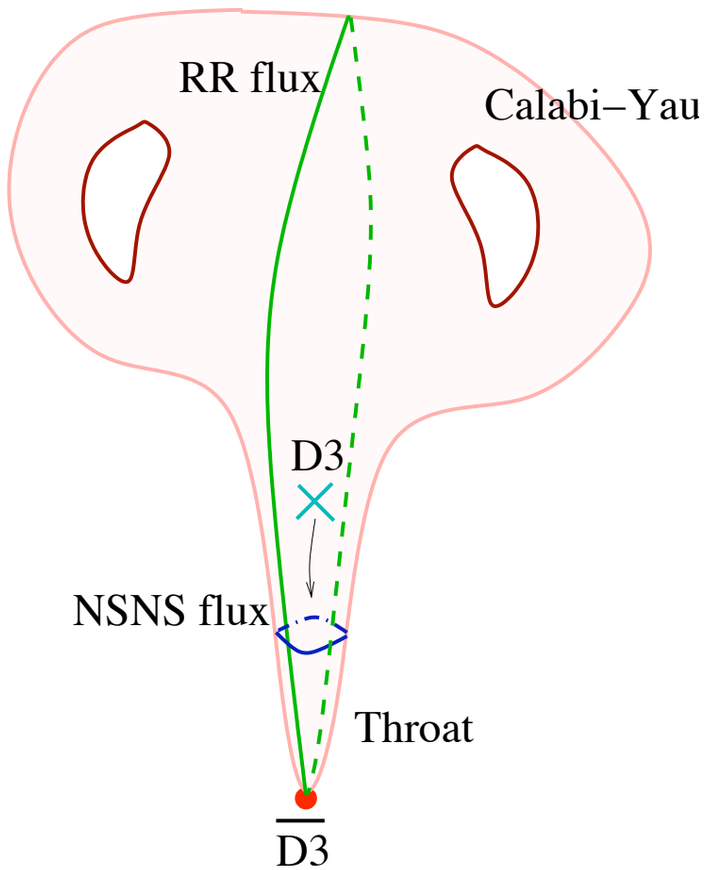

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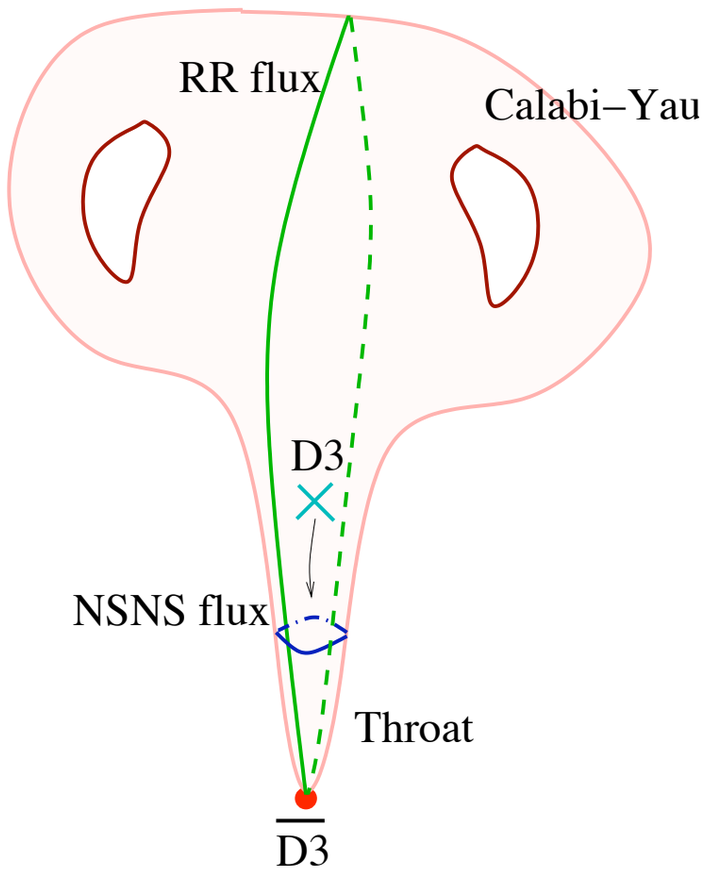


Warped D-brane World

• D-brane world scenario: Standard Model particles live on a D-brane (open strings). Gravity propagates in all dimensions (closed strings)

• Brane positions, associated to open strings, are scalar fields from 4D point of view.

• Compactification process introduces several scalar fields associated to sizes and shapes of compact manifold X6 (closed strings).

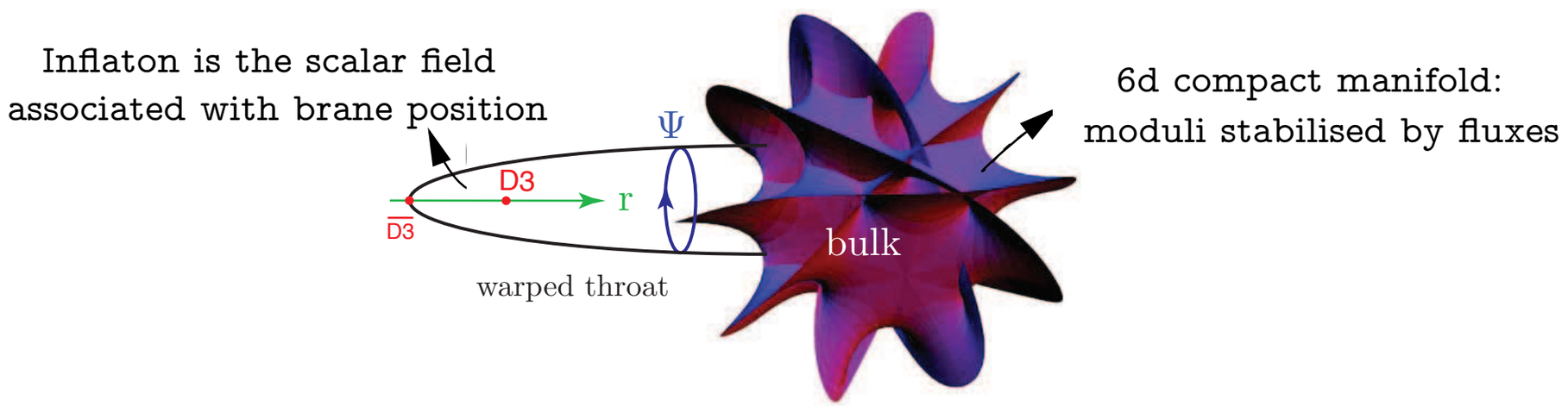
• Internal gauge fields (fluxes) give masses to dangerous moduli fields ⇒ warped compactification

[Giddings-Kachru-Polchisnki '01]

Application to cosmology: D-brane Inflation

D-Brane Inflation

• A D3-brane moves through a warped space. Internal fluxes help stabilise dangerous light scalar fields. [Kachru et al. '03].



• D-brane position(s) play role of inflaton(s)⇒ Geometrical interpretation of inflaton. Scalar potential generated due to anti-D3-brane at end of throat.

• Two different scenarios (generically multifield inflation):

✴ Slow roll inflation: flat potential required. Standard predictions for single field case $n_s \sim 0.96 \quad r \ll 1 \quad |f_{NL}| \ll 1$. Multifield dynamics also arises. [Kachru et al. '03].

$$S \supset \int d^4x\sqrt{-g_4}\left[\frac{M_p^2}{2}R + \partial\phi^i\partial\phi^j g_{ij} + V(\phi^i) + \dots\right]$$

✴ DBI inflation: no flat potential is required. Inflaton Lagrangean charachterised by non-canonical kinetic terms. [Silverstein-Tong '04]

$$S \supset \int d^4x\sqrt{-g_4}\left[\frac{M_p^2}{2}R + P(X^{ij},\phi^i) + \dots\right]$$

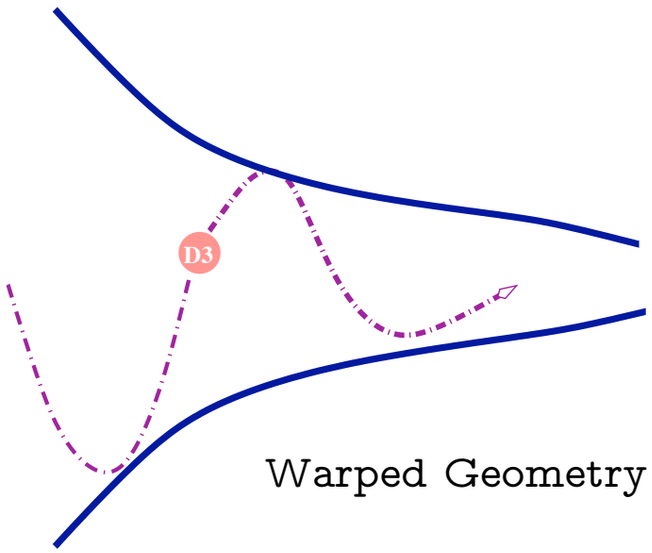
DBI Inflation and its signatures

- D-brane motion in internal 6D space described by Dirac-Born-Infeld + Wess-Zumino action ⇒ multifield cosmological evolution

[Easson-Gregory-Mota-Tasinato-Zavala '07]

$$S_4 = \int d^4x\sqrt{-g}\left\{\frac{M_{Pl}^2}{2}R - \left[h^{-1}\sqrt{1 - h\,\dot{\phi}^n\,\dot{\phi}^m\,g_{mn}} - h^{-1} + V(\phi^l)\right]\right\}$$

$$M_{Pl}^2 = V_6/\kappa_{10}^2 \qquad \kappa_{10}^2 = (2\pi)^7 g_s^2 \alpha'^4$$



- Non-standard kinetic terms give rise to speed limit for D-brane motion in compact space $h^{-1} > \dot{\phi}^2$

  - Combined with strong warping ⇒ accelerating trajectories without requiring a flat potential (cf. slow roll)

- DBI cosmological signatures:
  - Enough inflation requires brane to move close to speed of light: $c_S^2 \ll 1$ where $c_S^2 = (1 - h\dot{\phi}^2)$
  - Small sound velocity implies large departures from Gaussian spectrum. Quantified by non-negligible bispectrum $\langle\zeta\zeta\zeta\rangle \sim f_{NL}\langle\zeta\zeta\rangle^2$

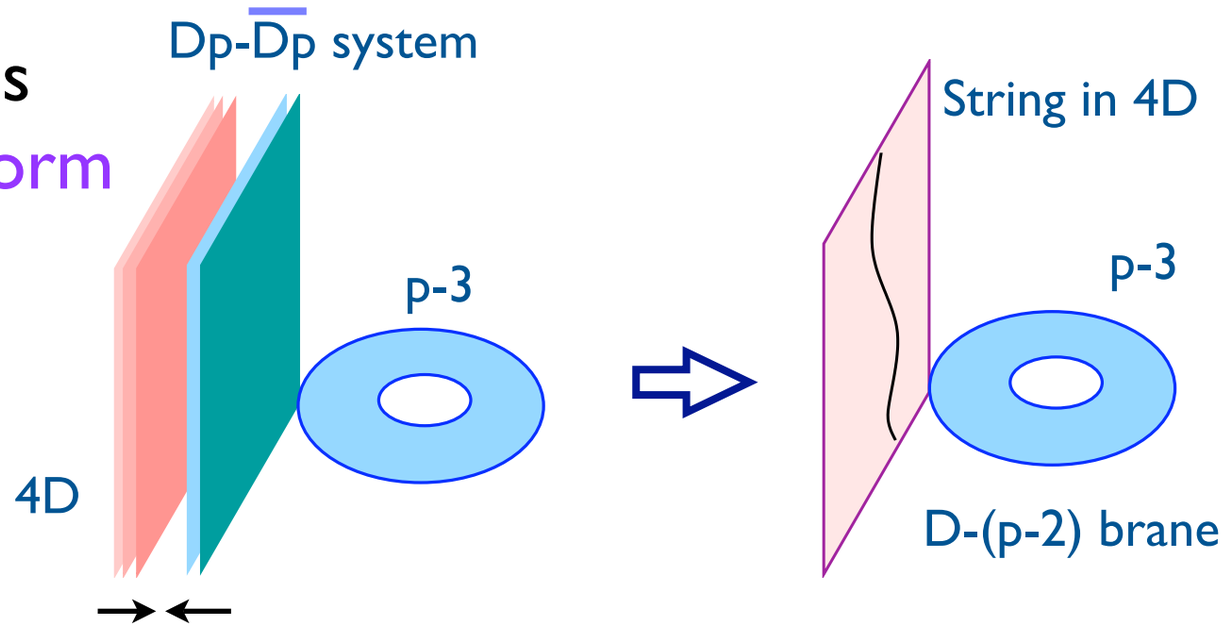
$$f_{NL} = -\frac{1}{3}\left(\frac{1}{c_S^2} - 1\right)$$

$$-114 < f_{NL} < 166 \quad (68\%cl\ 1\sigma) \implies c_S^2 \gtrsim 3\times 10^{-3}$$

  - In Wilson line case also observable gravitational wave spectrum can be generated $0.16 \lesssim r \lesssim 0.24$ [Avgoustidis-Zavala '09]

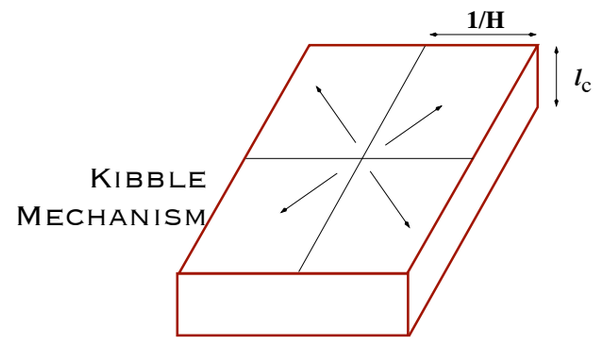
Cosmic superstring production at end of D-brane inflation

• A key side effect of D-brane inflation is the formation of cosmological defects form due to Dp/$\overline{\text{Dp}}$ annihilation. [Tye et al. '02]



• When Dp-$\overline{\text{Dp}}$ collide D(p-2)-branes form.

• Topologically, a variety of defects may be produced at end of inflation: domain walls, cosmic strings, monopoles.



• Cosmologically, only strings can form via Kibble mechanism in 4D: D-strings, F-strings, bound states.

• Dimensionless tension depends on type of string formed. A spectrum of tensions for cosmic superstrings arises (cf. field theoretic strings):

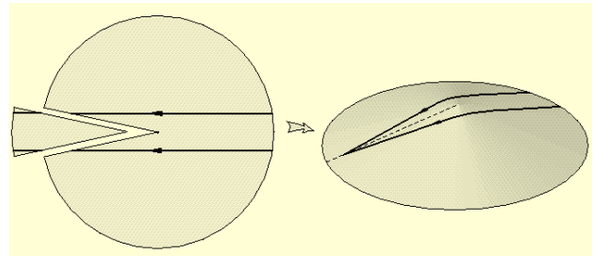
$$10^{-12} \lesssim G\mu \lesssim 10^{-6}$$

String theory in the Sky?

Cosmic strings can be detected via gravity, rather than particle physics:

- Gravitational lensing. Requires appropriate alignment of source behind string.

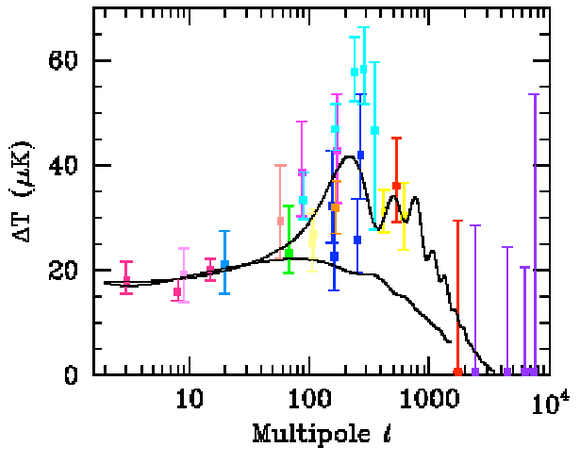
  Some candidates, no detection.



$$\delta = 8\pi G\mu$$

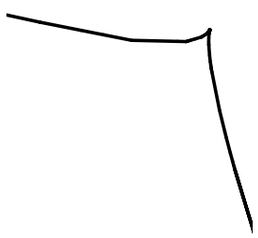
- Gravitational perturbations

  CMB: $G\mu < 10^{-7}$ Pulsars: $G\mu < 10^{-6}$



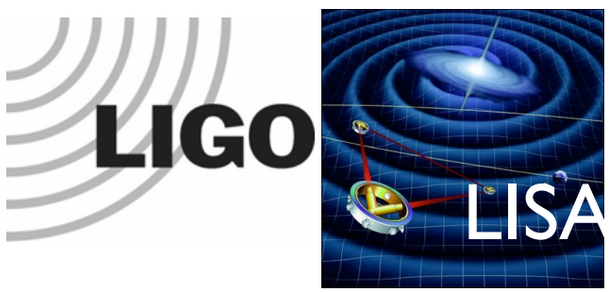
- Gravitational waves. Distortions of spacetime.

  Gravitational wave bursts are produced by cusps, points at which the string reaches the speed of light. Possible detection at LISA, LIGO.



Cups formation in a loop

Act as a strong source of gravitational radiation

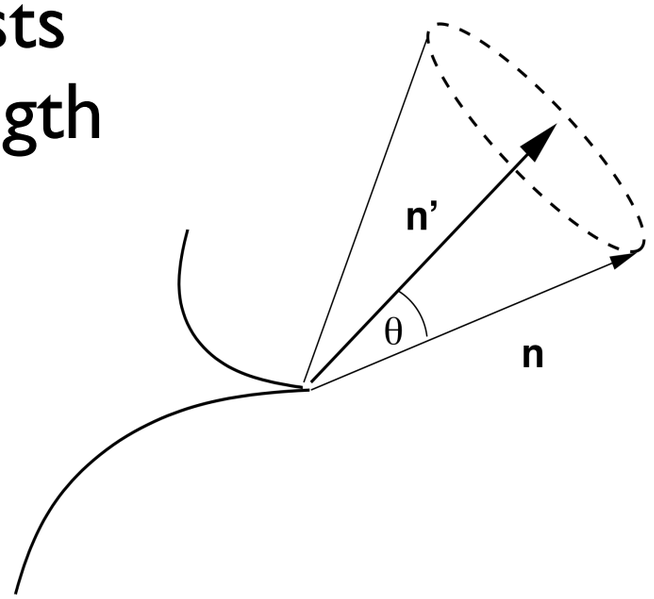


Gravitational Wave Signal (4D)

[Damour-Vilenkin (DV) '00-'05]

• Cusp beams out a strong pulse of gravitational radiation in a cone centered on the cusp.

• The form and amplitude of cusp gravity wave bursts can be computed as a function of mass per unit length of the string.



• The resulting cusp wave form has a power low behaviour in frequency.

• If cosmic string arise form D-brane inflation, it moves in (4+n) dimensions

⇓

what is the effect of extra dimensions on the cusp wave form?

Effects of extra dimensions in gravitational wave bursts (GWB)

- Extra dimensions reduce the probability of intercommutation
  $P \lesssim 1 \Rightarrow$ improve signal [DV '05]

- But also the kinematics of strings is different:
  [O'Callaghan-Chadburn-Geshnizjani-Gregory-Zavala '10]

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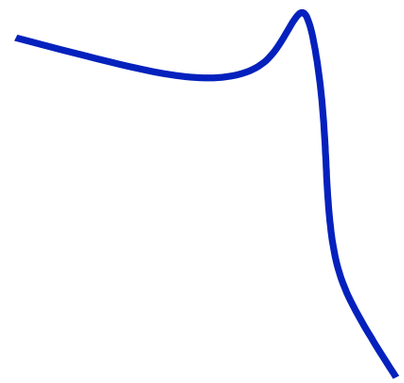

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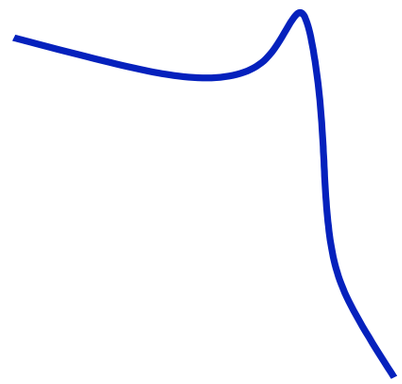

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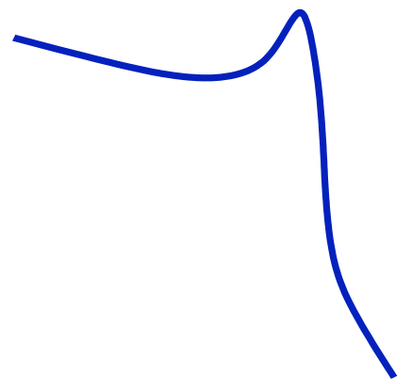
  - Amplitude depends on number of extra dimensions



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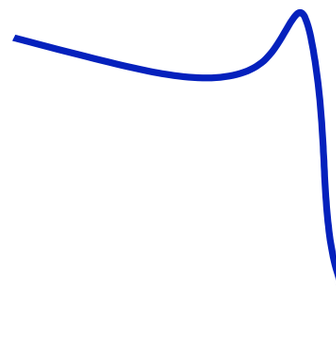

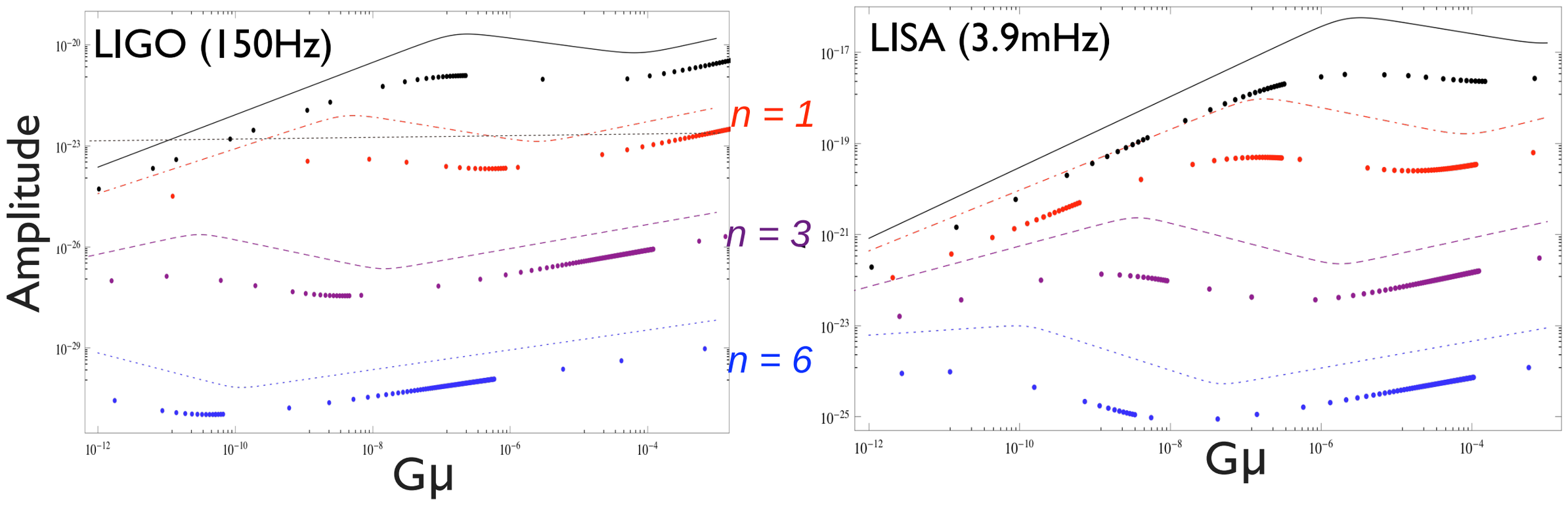

Summary

✳ String theory is very powerful guiding tool to investigate physics beyond standard models of Cosmology (ΛCDM) and particle physics.

✳ D-brane Inflation Models.

- Distinctive features from generic models with more than one field, such as non-Gaussianities, isocurvature perturbations, detectable tensor perturbations.

- End of inflation. Can give rise to detectable cosmic superstrings.

✳ Other stringy inflationary models:

- Closed string modulus plays role of the inflaton: modular inflation.
- Slow roll inflation with one or more fields.
- No D-branes involved ☞ no cosmic superstrings!